Next Generation Modeling for Deep Water Wave Breaking and Langmuir Circulation

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LONG-TERM GOALS

The long-range goal is to improve our ability to understand and predict surface waves, wave breaking, and the transfer of momentum between the atmosphere and ocean.

OBJECTIVES:

The objectives of our research are to use two free-surface, three-dimensional, turbulent, computational fluid dynamics models to investigate and quantify the interaction between surface waves and upper ocean turbulence.

The models are to be tested in comparison with equivalent laboratory experiments conducted in the ASIST (Air-Sea Interaction Salt-Water Tank) facility at RSMAS of wave energy dissipation and momentum flux. A suite of non-intrusive techniques including Particle Image Velocimetry (PIV), laser elevation gauges (LEG), an Imaging Slope Gauge (ISG) and infrared imagery are to be used.

Specific objectives include quantifying the exchange of wave momentum into average currents via breaking, quantifying the vertical distribution of momentum flux, and determining the influence of pressure forces on the surface.

APPROACH:

Surface waves remain one of the least understood dynamical systems in the ocean/atmosphere system. Although we generally know how waves are formed, we do not have a firm knowledge of how momentum from the atmosphere is transferred to waves via pressure forcing and how it is ultimately deposited in the ocean through wave breaking for different sea states. Breaking events generate isolated, near-surface current jets that can directly force turbulence by setting up wave-scale turbulent eddies. Interaction between these currents and waves also force turbulence through small-scale Langmuir circulation and direct interaction with orbital wave velocities.

Quantifying the growth and impact of surface waves is needed if we are to improve air-sea interaction in forecasting models. For example, prediction of wave growth requires parameterization of wave breaking so that wave amplitudes can be accurately estimated. Breaking events are also key elements in the transfer of momentum from the atmosphere to the ocean and act as sources of turbulence in the ocean mixed layer. These effects are not typically included in numerical ocean models, even though the ocean mixed layer is strongly affected by surface wave interaction with ocean currents.

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14. ABSTRACT
The objectives of our research are to use two free-surface, three-dimensional, turbulent, computational fluid dynamics models to investigate and quantify the interaction between surface waves and upper ocean turbulence.

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Observations and theory suggest that surface gravity waves are key elements in momentum transfer between the ocean and atmosphere. Waves initially form on the ocean surface in response to tangential surface stress between the fast moving atmosphere and the relatively stationary ocean. Pressure form drag is produced by surface waves obstructing the wind, and quickly surpasses the frictional stress as the main momentum exchange processes between the ocean and atmosphere. Increasing wave heights eventually lead to wave peaking and breaking events, which transfer momentum from the wave field to the upper ocean currents, completing the exchange of momentum between the atmosphere and ocean. Further interaction between the surface wave field and upper ocean current shear produce Langmuir circulation which facilitates the transfer of momentum from the surface layer to the bottom of the mixed layer.

Many specific details of this conceptual model are unknown and are ignored in surface exchange parameterizations. For example, typical models of the ocean surface boundary layer assume that momentum is transferred to the ocean through a spatially average wind stress, thereby generating a horizontally uniform current. Surface wave effects are parameterized as the rectified interaction of the wave field on this uniform current (e.g. Craik and Leibovich, 1976). We find, however, that using this approach produces surface current perturbations (via Langmuir circulation) that are too small in comparison with observations (Smith, 1999). A possible explanation for the model error is the contribution of momentum by surface wave breaking. In general, we do not know the strength of currents produced by individual breaking events, or the depth and horizontal scales of these current "patches." If surface currents generated by breaking are sufficiently strong, then upper ocean turbulence could be greatly influenced by these patches, both in strength and in the scale of turbulent eddies. A better understanding of how wave breaking converts wave momentum to surface currents is essential if we are to improve models of waves and ocean-atmosphere momentum exchange processes.

Open-Ocean Modeling

Experiments on open-ocean conditions with wave breaking have been conducted using the VOF technique discussed previously. Results from these experiments have shown strong interaction between breaking waves and surface currents, with significant secondary circulations. This modeling approach is designed to more nearly replicate open ocean wave conditions. We have simulated a horizontally periodic domain without rigid walls, so that the longer time evolution of the momentum transfer between the breaking waves and the wave generated upper ocean shear flows can be examined. In this model the waves propagate across the domain for many wavelengths and wave periods. Simulations have been conducted that examine both small and large amplitude waves. Small amplitude waves produce the forcing of Langmuir circulation. For these, our results agree with theoretical predictions given in Craik and Leibovich (1976), validating the general theory for the Stokes drift vortex force interaction between waves and surface currents. Larger amplitude waves produce significant breaking and nonlinear interaction between surface currents and waves. Our results for higher amplitude breaking waves yield similar momentum transfer from waves to mean currents that generate longitudinal circulations.

Our approach for studying surface waves and upper ocean dynamics relies on a combination of numerical modeling and laboratory tank experiments. Modeling has focused on two research thrusts, one centered on modeling air-sea wave interaction for laboratory wave systems, and the second aimed at simulating wave breaking in an open-ocean environment. Both methods have employed a volume of fluid (VOF) technique for simulating the free surface. For short duration, low amplitude wave

simulations this method captures significant wave dynamics and interaction of the atmosphere with the wave system. However, we have found that longer term simulations (greater than 10 wave periods) or breaking events place a more stringent requirement on the VOF method, resulting in signicant errors caused by numerical dissipation in the mean momentum budget. Consequently, for wave breaking experiments we are proposing to conduct longer duration experiments using a Lagrangian particle based wave model, for example, as described in Dalrymple and Rogers (2001).

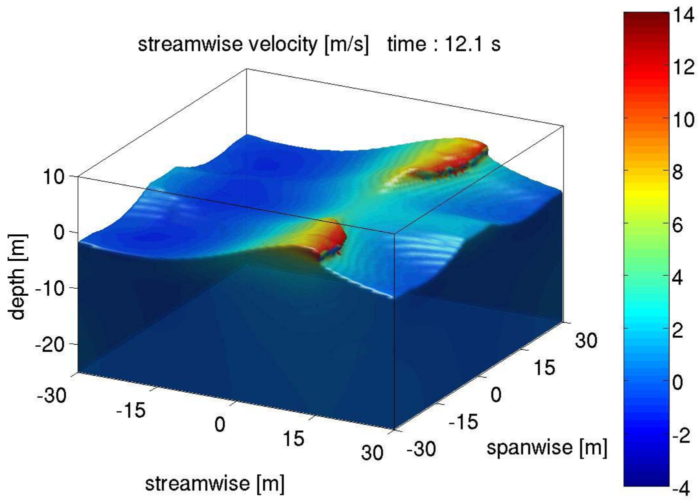

Figure 1. Simulation of a variable height wave system initialized with the wave height maximum of 5 m in the center of the domain for a single wave component using the VOF model. Wave breaking begins in the middle and propagates in the cross stream direction to the edge of the domain.

An example of one simulation is shown in Figure 1. This simulation was performed over a 256 x 256 x 64 grid point domain. The model is able to simulate currents associated with the orbital wave velocity, average streamwise velocity, and perturbations associated with wave/mean current interaction or Langmuir circulation (LC). Formation of LC is quite rapid, taking less than 3 minutes from the start of the simulation. Qualitatively, these results are very encouraging, for example, by showing alignment with the mean wind stress, circulation mergers or Y-junctions as reported in Farmer and Li (1995), and overall structure similar to observed LC (Thorpe 2004). Here we have initialized a wave "bump," which propagates primarily in the streamwise direction, but has secondary waves that move transverse to the wave front, meeting at the edge of the domain. When the waves meet, the amplitude exceeds the breaking limit causing a wave breaking patch to form along the model periodic boundary.

Breaking in this case does not spill down the wave front, but instead generates a surface jet of fluid representing a transfer of momentum from the wave system to the mean ocean currents. This momentum transfer can generate secondary circulations and turbulence via two processes. First, because the breaker has a limited area, lateral shear is generated along the edges of the breaker jet. Shear generation of turbulence is likely in this scenario and will augment the direct formation of turbulence created by the breaking event. The second source of circulations is the interaction of the remaining wave system with the new surface currents, which will produce LC and the wave propagates over the breaker momentum patch.

Although we have been successful in simulating multiple wave periods and strong LC in the VOF model, we have not been able to overcome problems with the momentum budget. The model conserves mass, however, momentum conservation becomes an issue whenever water enters or exits a grid box. The first order approximations to the spatial derivatives that are necessary to use across the free surface inherently include undesirably large amounts of numerical damping. For example, when water enters an empty grid cell, velocities are needed to maintain non-divergent flow. Otherwise, the model mass field will change. Typical methods for assigning new velocities include setting a zero gradient condition or interpolating velocities from surrounding grid cells that have fluid. Unfortunately, these methods do not ensure momentum conservation. For breaking events, errors in total momentum are enhanced because the wave velocity is a maximum in the region of the domain with the greatest number of grid cells flooding with new water. Decreases in the average momentum can be as large as a factor of 2 for breaking events as momentum is lost at the wave front.

Because of these problems, we have begun researching alternative methods for modeling surface waves. One promising approach is the Smooth Particle Hydrodynamics (SPH) method pioneered by Monahan (1992). Fluid motion in SPH is simulated by solving the Langragian equations of motion along with an equation of state that links particle density to pressure. Momentum and mass are carried by each particle, ensuring conservation. SPH is especially well-suited for modeling complex free surface flows because it does not depend on a grid structure and easily allows for sections of the fluid to separate and reconnect, without having to deal with a free-surface boundary condition.

Gesteira et al. (2007) recently released a publicly available version of their SPH model, referred to as SPHYSICS, which implements free surface flow problems for a variety of scenarios. An example is presented in Figure 9 for a wave generator case.

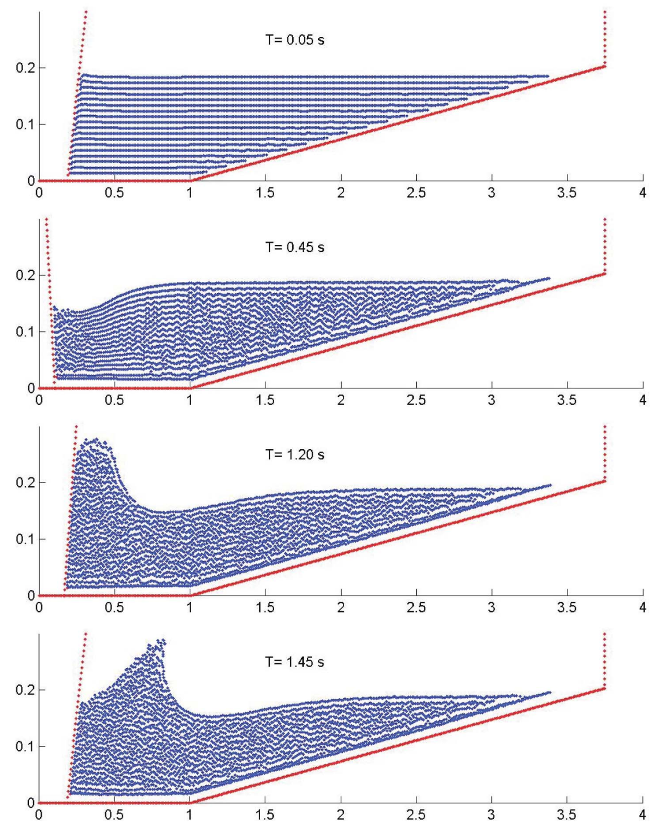

Figure 2. Simulation of a wave generated by a wavemaker along the left boundary of the domain. The SPHYSICS model solves the Lagrangian eqations to predict the motion of particles and as such does not require a grid structure.

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